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HUMAN FACTORS ISSUES IN TELEROBOTIC SYSTEMS FOR SPACE STATION FREEDOM SERVICING

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Abstract

This paper describes requirements for Space Station Freedom servicing and defines the state-of-the-art for telerobotic system on-orbit servicing of spacecraft. The paper also identifies the projected requirements for the Space Station Flight Telerobotic Servicer (FTS). Finally, the human factors issues in telerobotic servicing are discussed. The human factors issues are basically three: the definition of the role of the human versus automation in system control; the identification of operator-device interface design requirements; and the requirements for development of an operator-machine interface simulation capability.

Space Station Freedom Servicing Modes

One of the elemental capabilities to be provided on Space Station Freedom is the on-orbit servicing of spacecraft, satellites, payloads, and Space Station elements. Servicing includes all activities associated with restoring the operational capability of a system including fault identification and diagnosis, planned maintenance, and corrective maintenance. Specific servicing tasks include inspection, fault isolation, refurbishment, removal and replacement of components, checkout, test and calibration, cleaning, tightening, adjusting, and repair.

Alternate servicing modes being considered for Space Station Freedom include astronaut extravehicular activity (EVA), telerobotic systems, and automated servicing. EVA involves servicing by an astronaut at the worksite. Telerobotic servicing involves operations controlled by a human from a location remote from the worksite. Automated servicing involves performance of servicing activities in a purely autonomous manner with no human involvement.

EVA for spacecraft servicing is a proven technology with the results of Skylab sun shield deployment and Solar Max maintenance. The advantages of EVA as a technique for servicing Space Station Freedom as compared with the other alternatives include: 1) EVA is the furthest advanced of the alternate modes in terms of validated technology; 2) EVA is the most flexible of the modes and makes fewest demands on the design of the systems being serviced; 3) the astronaut is at the worksite bringing to the task all the adaptability and flexibility inherent in human decision making, adaptive reasoning and problem solving; and 4) since interior Space Station Freedom servicing will probably be accomplished in large part by a human technician, the only functional difference between IVA and EVA servicing is the constraint of performing EVA in the pressurized suit. Disadvantages of EVA include: 1) demand on astronaut time; 2) less than optimum applicability to repetitive tasks, 3) impacts on astronaut safety; and 4) associated astronaut support requirements such as life support, workstations, lighting, tools, and astronaut training.

Telerobotic servicing has been accomplished in earth applications, such as in the hostile environments of undersea worksites and nuclear power plants. Telerobotic servicing has not been performed in space as of yet. Advantages of the telerobotic servicing mode include: 1) availability of human decision making, adaptive reasoning and problem solving without the additional hazards associated with placing the human at the worksite; 2) reduced demands for human operator time as compared with EVA; 3) ability to perform in conjunction with the other modes (combined

EVA and telerobotic servicing, and servicing tasks involving both human remote control and automated control); 4) the capability for fully repetitive actions; and 5) its ability to perform servicing tasks simultaneously with a number of other telerobotic servicing systems. Disadvantages of telerobotic servicing systems include: 1) limited capability (dexterity, reach, controllability) associated with existing telerobotic technology; 2) demands on the human operator; 3) demands placed on the design of interfaces between the telerobotic servicing system and the system being serviced; and 4) additional servicing requirements for servicing of the telerobotic system itself.

Automated servicing in terms of selecting redundant systems and automated fault detection has always been provided on manned and unmanned spacecraft. Capabilities associated with component removal and replacement, inspection, and repair in strictly an automated mode have not been developed for space missions. The advantages of automated servicing include: 1) minimal demands for crew time; 2) minimal impact on crew safety; 3) capability to perform repetitive and rote tasks continually; and 4) its inherent relationships with artificial intelligence and adaptive control. Disadvantages of automated servicing include: 1) technology advancements needed to make the mode viable; 2) loss of adaptability and flexibility in servicing operations and spacecraft design; 3) constraints placed on the design of the system to be serviced.

The investigation of The Human Role in Space (THURIS) conducted by McDonnell Douglas for Marshall Space Flight Center in 1984 categorized the alternative modes for on-orbit satellite servicing as follows:

- manual - unaided EVA with simple non-powered hand tools;
- supported - EVA servicing using supporting machinery or facilities to accomplish assigned tasks (e.g., manned maneuvering unit);
- augmented - EVA with human sensory or motor capabilities augmented (e.g., powered tools, exoskeletons, and inspection aids);
- teleoperated - use of remotely controlled sensors and actuators enabling the removal of the human from the worksite while maintaining direct manual control over the servicing activities;
- supervised - replacement of direct manual control of system operation with computer-directed functions in a supervisory control manner;
- independent - independent, self-actuating, self healing operations requiring a minimal of human intervention.

Telerobotic Servicing System (TRS) Description

At present, the level of robotics and teleoperator technology would probably support applications envisioned by NASA as far as physical performance of necessary functions is concerned. Insofar as a telerobotic approach is required to achieve mission objectives, however, great demands would probably be placed on the system operator in terms of skills and workload. Generally, a robot is distinguished from a telerobotic system in that the former can perform tasks under autonomous local control while the latter requires some level of direct real-time control by a human operator. Remote control by an operator in turn generates requirements for a large amount of information to be fed back from the device and displayed to the operator. The necessary manual controls and the correspondence between controls and manipulator effectors can generate demanding operator tasks in terms of skill levels and of task time and workload factors.

An index of the efficiency of a telerobotic system including all necessary subsystems and control laws is the ratio of time to perform a given task under operator control to the time taken by a human subject to perform the same task by hand. This metric was originally proposed by Vertut, Papot and Rossignol (1973). These authors reported telerobotic to manual time ratios ranging from 1.5 to 100 depending on teleoperator system parameters and motion direction within the reach space for a task involving precise end effector placement and orientation. The system used by Vertut et. al. provided direct vision of the manipulator and task apparatus by the operator. Kirkpatrick, Shields, Malone and Brye (1977) reported time ratios ranging from 21 to 33 for an extendable stiff arm manipulator and from 63 to 127 for an anthropomorphic manipulator with resolved rate control. Both systems provided orthogonal video views of the manipulator and task board. Depending on particulars of the manipulator configuration, the visual feedback system and the control scheme, therefore, available data suggest that teleoperation may be from 1.5 to over 100 times slower than manual performance of the same task.

Another comparison index for teleoperation versus manual performance of a positioning task involves Fitts' Law (Fitts and Posner, 1967). This law posits a linear relationship between mean movement time and a measure called the index of difficulty which involves the distance and terminal accuracy of a movement. The reciprocal of the slope in the Fitts' law equation can be interpreted as the number of bits of information processed per unit time. When highly practiced subjects perform positioning tasks, a typical result is an information processing rate on the order of 12 bits per second (Fitts and Posner, 1967). Corresponding calculations performed by Kirkpatrick et. al. (1977) using the teleoperator system performance data described previously yielded information processing rates which ranged from 0.07 to 0.74 bits per second. Clearly, even with considerable practice, the act of directly controlling a multiple degree-of-freedom manipulator in real time is inherently difficult.

On the other hand, very effective industrial robots are routinely used for a variety of manufacturing tasks. These cases, however, involve many repetitions of precisely specified movements. When robot technology is applied to manufacturing tasks such as spot welding, for example, the necessary end effector moves and corresponding joint moves are identified in precise detail and the robot is programmed specifically to execute these in a suitable sequence and generally in an open-loop fashion. Such a robot can operate autonomously under an automatic control law and can be fast. It has zero adaptability, however, and must be re-programmed if the task is changed.

These considerations suggest a continuum of human versus automated local control of a telerobotic system. At one end of the continuum would be a pure robot, pre-programmed to execute a few precisely defined movement sequences under automatic control. At the other end would be a pure teleoperator with direct and continuous human control of the manipulator joint angles. The latter system would be adaptable to new tasks and conditions because the human operator exercises a generic level of control and can modify his/her command sequences to adapt to new task requirements or changed task conditions.

The state-of-the-art in telerobotic systems and equipment for spacecraft servicing was identified in the NASA JSC Servicing Equipment Catalog (JSC-22976, 1988). The specific items in the catalog having implications for telerobotic servicing of the Space Station are listed below:

<u>The Flight Support System/Servicing Aid Tool (FSS/SAT)</u> is a remotely-operated bilateral force-reflecting manipulator system. It will enhance the capability of the NSTS Mission Specialists to perform IVA and EVA Free-Flyer Spacecraft servicing in the Space Shuttle Cargo Bay from the Aft Flight Deck. The system, which mounts to the FSS by a versatile electro-mechanical interface, can be repositioned by use of the remote manipulator system. The FSS/SAT will have provision to pickup and restow tools from a tool storage locker mounted on the FSS. The FSS/SAT will either be stowed in a storage rack or will be secured to the FSS during launch and landing operations. The system is designed to operate from the Space Shuttle onboard utilities.

<u>The Light-Weight Module Service Tool (LW/MST)</u> is a device to permit remote on-orbit exchange of On-orbit Replaceable Units (ORUs) when coupled to an automated servicer system. It is been redesigned for use with the Orbit Maneuvering Vehicle, Flight Support System/Servicing Aid Tool, Remote Manipulator System, other manipulator and robotic servicers. This tool will permit on-orbit exchange of spacecraft module, payloads, and instrument orbital replacement units. Remote computer or manipulator control is retained to permit the servicing operations to be performed from the Shuttle Aft Flight Deck.

<u>The Orbital Maneuvering Vehicle (OMV)</u> provides for the extension of payload services and capabilities out of the Orbiter and the Space Station. These services include spacecraft delivery and retrieval to and from higher orbits, reboost or deboost, payload viewing and satellite support. The OMV will also be capable of supporting advanced mission kits for remote servicing, refueling, and debris retrieval. On-orbit-operations may be controlled either from the ground or the Space Station. Space Stations operations typically will be controlled by the Space Station operator when

the OMV is operating in close proximity to the station. In either case, final docking maneuvers are performed in remotely piloted modes.

The Orbital Spacecraft Consumables Resupply System (OSCRS) is designed to be flexible in order to service a wide range of satellites and be adaptable to support Space Station. OSCRS will also provide adequate data and control to permit independent crew operation/trouble shooting/work-around without ground coverage.

The Payload Berthing System (PBS) provides on-orbit docking/berthing of payloads for servicing, repair or temporary holding. The PBS is sidewall mounted at the primary attachment locations of the cargo bay.

The Payload Interface Mechanism (PIM) mounts on top of the Manipulator Food Restraint (MFR) stanchion. It is a tethering device for attaching a payload to the MFR and consists of three main parts: a payload fitting, a pyramid fitting, and a pyramid housing. The pyramid fitting and the pyramid housing are connected by a retractable tether. Tether attachment rings are provided on the ends of the pyramid fitting's handles and on the payload fitting.

The Remote Manipulator System (RMS) is a mechanical arm which augments the Shuttle systems in performing the deployment and/or retrieval of a payload. In addition, the RMS may be used to perform other tasks in support of satellite servicing or to assist in extravehicular activities. The manipulator arm consists of four joints connected by structural members to a payload-capturing device called an end effector. The movement of the arm is controlled by an operator using a display and control panel and two three-degree-of-freedom hand controllers. The operator also has visual access through the windows in the Aft Flight Deck. The manipulator arm is anthropomorphic by design, comprising shoulder pitch, shoulder yaw, and elbow pitch joints (mainly providing end-point translation) plus wrist pitch, yaw, and roll joints (providing rotation of the end effector).

The Remote Manipulator System Module Servicing Tool (RMS MST) is a device to permit remote on-orbit exchange of On-orbit Replaceable Units (ORUs) when it is coupled to the RMS. It develops high torques up to 160 ft-lbs, with provision for torque takeout and transporting of Multimission Modular Spacecraft (MMS) and other compatible ORUs. The tool is controlled and operated from the Space Shuttle Aft Flight Deck. The RMS MST is modeled after an EVA astronaut operable tool used for the same purpose.

The RMS-Based Handling and Positioning Aid (RMS/HPA) is a mechanical arm which provides a wide range of adjustable work stations both inboard and outboard of the Orbiter Cargo Bay. It is derived from Remote Manipulator System (RMS) technology.

Servo-Actuated Manipulator System With Intelligence Networks (SAMSIN) is a bilateral force reflecting master-slave servo manipulator. SAMSIN is a general purpose electrical-mechanical device. SAMSIN is used to extend the hand and arm manipulative capacity into a "remote hostile" environment. A master-slave manipulator is an extension of the human hand. The remote hand may be used as a tool, but can be used more effectively as the hand that holds and guides a tool. SAMSIN has seven degrees-of-freedom and is bilateral and force reflecting in all degrees-of-freedom.

The Stabilized Payload Deployment System (SPDS) is a dual redundant motorized system designed to deploy RMS type payloads up to 50,000 pounds that are typically secured in the bay with "Port" side and starboard Payload Retention Latch Assemblies (PRLA's) and Active Keel Assemblies (AKA's).

The Standard End Effector (SEE) is the terminal device on the Remote Manipulator System (RMS) arm, and its prime function is to capture, hold, and release payloads. The SEE is a hollow, light-gauge aluminum cylinder which contains a remotely controlled motor drive assembly and three wire snares. The SEE drive system provides the abilities both to capture and release and to rigidize a payload. The SEE is controlled from the RMS control panel in the Aft Flight Deck of the Orbiter.

The Universal Servicing Tool (UST) is a flight power tool that allows changeout of the tool attachments on orbit. Designed to anchor itself to a payload, spacecraft module, or orbiter, the UST can be used to remove or tighten bolts, and operate latches and fasteners while reacting the resulting torque to the anchor points. The UST comprises a control module, a drive module, and interchangeable tool elements. The UST can be operated manually by an astronaut (as a NASA Goddard Space Flight Center version was used on the Solar Maximum Mission SMM), or operated remotely when attached to a manipulator arm.

Telerobotic systems capable of performing the necessary on-orbit servicing functions will probably require at least four general capabilities as follows:

- mobility providing transit aboard or around the Space Station. This capability will be provided by a free flying maneuvering vehicle such as the OMV, or by dexterous manipulator systems mounted to rails attached to the Space Station, or by being capable of being moved and installed at specific attachment points on the exterior of the Space Station or Space Station elements
- manipulation involving multiple degree-of-freedom manipulator arms and end effectors suited to the required servicing activities
- sensing and communications to provide sensor feedback to the remote system operator concerning the task in progress, navigation data, environmental data, and manipulator/end effector status, position and orientation data
- control and computational which directs motors or other effectors in the mobility and manipulator subsystems according to automated control schemes, operator commands, or some combination of the two.

Space Station Flight Telerobotic System (FTS)

The FTS is designed to be a teleoperated device controlled by a crew member from within the Space Station itself or the National Space Transportation System. Limited autonomous capability is projected. The two principle components are the telerobot and workstations. The FTS will require transportation to and from worksites. This will be available from the Mobile Transporter, the Mobile Servicing Center, and EVA crew members. The FTS will rigidly stabilize to the worksite, and all structural loads will be transferred to the worksite. Power, data, and video accomodations will be available either at the worksite or from the FTS. The FTS will be useful for missions that are outside the safety envelope for human operators. Scenarios requiring excessive strength, reach, and duration may be better accomplished with the FTS. The FTS will be capable of detecting failures and automatically safing. In addition, an EVA crew member will be able to shut down the telerobot with a redundant direct link. The telerobot is designed to be operable by one person at the workstation; bilateral force reflection between the telerobot and the hand controller shall be provided. Man-machine interfaces necessary for control of the telerobot will be designed into the system.

An example mission for FTS Space Station servicing was described by Malone and Permenter (1987 and 1989) who assessed the requirements for FTS servicing of the Gamma Ray Observatory (GRO). The GRO refueling mission involves capturing the satellite with the Remote Manipulator System (RMS), placing it on the Flight Support System (FSS), mating the refueling hoses, pumping the fuel, demating the hoses, grappling GRO with the RMS again, and returning her to orbit.

The fuel used to power the Gamma Ray Observatory is harmful to humans. The potential for coming in contact with the fuel during the refueling scenario has to be reduced. The refueling mission is a time consuming effort due to the fuel used to propel the satellite. Transferring the fuel too rapidly will cause it to heat up beyond acceptable temperatures.

Capturing GRO and placing her upon the FSS may require an extensive amount of time, producing the possibility that the refueling scenario will occur over a couple of days. The first day will be devoted to capturing the satellite, rotating it 180° and placing it on FSS with the help of a camera on the base of GRO. Refueling will then be accomplished on the second day of the mission.

Mating the couplings with FTS involves only one operator who remains inside the pressurized cabin. The movements of the robotic machinery are slow and awkward, yet more efficient than EVA operations which require excessive frontend preparations. The precision required when mating the couplings is difficult to achieve telerobotically, however the danger of exposure to the propellant makes FTS a likely candidate for the procedure. Refueling GRO by FTS operations takes 29.4 hours and involves one crew member. This crew member is working one-hundred percent of the time, and has completed one-hundred tasks by the time the satellite has been refueled.

Human Factors Issues in Telerobotic Servicing

The significant issues in human factors design of telerobotic systems for Space Station servicing are: definition of the role of the human in the control of the servicing operation; operator-telerobotic device interface design; and development of a simulation test bed to develop and validate operator-machine interface design approaches.

Definition of the Role of the Human

The issue in the determination of the role of the human in telerobotic systems control involves the development of alternate techniques for allocating system functions and subfunctions to human and machine performance. Specific allocation techniques will include:

- Allocations to man or machine
- Allocations of human operator functions among several operators
- Allocations to local or remote control
- Allocations to control modes ranging from automated to manual teleoperated control.

Feasible allocation approaches will be determined through an assessment of the expected effectiveness of each candidate approach in terms of system requirements. Where optimal allocation decisions can be made based on existing data, these decisions will lead to allocation concepts. Where additional data are required to complete the allocation, or to verify an allocation decision, a requirement for simulation data will be generated. Control modes include: 1) automated control, typical of industrial robots where the system performs in a completely pre-programmed manner; 2) adaptive control, wherein the telerobotic system learns to adapt to its sensed environment with tutoring from the human operator, thereby developing its own rules and algorithms; 3) supervisory control, wherein the system performs pre-programmed or adaptive routines and response under supervision of the human operator or executive software; 4) interactive control where the operator and the computer cooperatively share control authority under specific interaction protocols; and 5) manual teleoperated control.

The allocation of subsystem control functions to operator or machine should take advantage of capabilities including local autonomous action and supervisory control so as to lighten the burden on the human operator relative to the current level of activity and skill required in pure teleoperator systems.

Supervisory control implies one of or both of the following:

- A manipulator system performs the bulk of the movements required for a given task under local autonomous control laws. This performance is monitored by a human operator who assumes direct control only if required.
- A manipulator system has a series of subroutines which produce standardized "elemental moves." The operator commands the device during task performance by selecting and stringing together elemental moves.

Application of either or both of these closely related versions of supervisory control has considerable potential for reducing the burden on the operator of a telerobotic system and for increasing the speed and accuracy of task performance. Application of supervisory control techniques is expected to facilitate development of the remote telerobotics capabilities envisioned by NASA. The human factors issues inherent in the implementation of supervisory control for telerobotic systems were addressed by Malone, Kirkpatrick and Seamster (1988).

Identification of Operator-Device Interface Design Requirements

Operator-machine interface requirements will be developed for displays, controls, consoles, workspace, telepresence, communications, user-computer interfaces, and procedures.

- Displays
  - Situation displays (resource management, sighting devices, and detection aids)
  - Environment displays

    - video (stereo vs. mono, FOV envelopes vs. detail resolution requirements, pointing, integration, point of view)
    - special sensors (tactile, kinesthetic, motion detection, and proximity - obstacle detection)
  - Navigation displays
    - displays of arrangements (route planning, destination planning, geographic reference)
    - location, position and orientation of each manipulator
    - formation displays
    - standard routines (transit, evasion, positioning and orientation, synergistic formation, and stored movement sequences)
  - Status monitoring (temporal, diagnostics, and voice display)
  - Data base access displays
  - Communications displays
  - Expert system interface
- Controls (manipulator, mobility systems, sensor control, testing/troubleshooting, communications, navigation systems, mission data processing, and zero-g and operating envelope constraints)
- Consoles/panels (control and display arrangements, panel packaging, and zero-g and workspace volume constraints)
- Workspace (workstation, arrangements, seats/restraints, access/egress, windows, and safety devices)
- Telepresence (display integration, whole or part task, visual only or multisensory, panoramic or multiple camera viewing, and multisensor integration)
- Communications (mode control, status monitoring, link optimization, and uplink/downlink characteristics)
- User-computer interface (control authority, user-computer dialogs, continuous control, protocols, expert system interfaces, special displays, decision aids, and training modes)
- Procedures (sequences, job design, job aids, and decision rules)

Development of an Operator-Machine Interface Simulation Capability

While a considerable body of theory and research exists concerning autonomous, semi-autonomous and supervisory control, application of these techniques to the operator-machine interface of real systems is not routine and is not supported by a corresponding body of proven engineering and human factors practice. Therefore, it is viewed as essential to the applications envisioned that a man-in-the-loop simulation capability be developed to support evaluation of feasibility and effectiveness of advanced concepts for allocation of control functions to operators and machines.

Specific simulation requirements include such issues as degree of simulation fidelity, simulation data requirements, data acquisition and recording requirements, and data analysis requirements. The specific issues are: 1)Degree of simulation (whole task vs. part task, extent to which controls and displays are real, simulated or dummied, engineering simulation vs. prototyping simulation vs. procedures, and development simulation vs. training simulation); 2) Determination of simulation data requirements including type of data (Performance measures, control variables, and independent variables), data reliability requirements (experimental controls and independent variables), data validity requirements including sampling criteria for missions and conditions, operations and tasks, operators, and design concepts, and fidelity requirements; 3) Data acquisition and recording requirements including data acquisition instrumentation, data integration, and monitoring vs. measurement data; 4) Data analysis requirements including quick look analysis, performance analysis and trends, inferential statistics and descriptive statistics; 5) Simulation visual subsystem including view of manipulators from the perspective of the control station, view of the individual manipulators from the perspective of another manipulator, view of the target system from the perspective of a manipulator, and view of the Space Station from the perspective of a manipulator; and 6) Manipulator control simulation enabling simulated control of manipulator arms and end effectors with an integrated view of the worksite.

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